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DRAFT FINAL REPORT
DOT Project No.:
Contract Number: 693JK31810001

Improvements to Pipeline Assessment Methods and Models to Reduce Variance

Reporting Period:
February 1 2019 through April 30 2019

Report Issued:
April 26th, 2019

Prepared for:
U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration

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Executive Summary

The project continues to track on schedule and on budget. No major performance issues have been encountered. We continue to identify necessary improvements to the FEM analysis external model formulation that are needed to ensure convergence on the more advanced damage propagation models. Incorporating these improvements into the formulation is not hindering progress. We have also encountered minor issues on managing the FEM cluster in parallel batch mode. These batch management issues have been resolved together with COMSOL support in a timely manner up to this point.

All planned deliverables have been met this quarter. They are reported on in detail in the body of the report and are summarized here:

Uncertainty Quantification of Material Properties and Defects Phase 3 Report

GTI provided material test data to ASU who applied hierarchical modeling to develop distributions for true toughness and break strain. The modeling addressed material property variation within a single pipe and heterogeneity of the measured properties across groups of similar pipes.

Probabilistic Fracture Assessment Phase 1 Report

GTI and ASU collaborated intensively on this task with detailed discussion on how to best approach using uncertainty quantification methods to optimize the design of experiment approach employed in the FEM modeling process. The results of the FEM modeling are used to develop an efficient response surface model that can be used to predict the limit state of pipes with interacting defects and loads. A large number of FEM simulations are needed to develop these response surface models. ASU demonstrated an approach capable of significantly reducing the number of FEM simulations needed to develop the response surface model. The ASU approach utilizes a kriging methodology that determines the optimum placement of FEM simulations in the design space to minimize variance in the calculated response. GTI provided ASU fully developed response surface models based on thousands of FEM simulations. Both 2-D and 3-D response surfaces were provided.

The trial data sets provided to ASU were:

- 2-D DoE on steel pipe with infinite axial crack (515 runs)
  - ASU UQ process reduces the number of necessary runs to 70
- 3-D cast-iron bending with flaw (11,376 runs)
  - ASU UQ process reduces the number of necessary runs to 510

The kriging approach developed by ASU resulted in significant reductions in the number of simulations needed. GTI will incorporate this method into the upcoming FEM simulation process.

FEM DoE Phase 1 Report

Phase 1 of the FEM Design-of-Experiment (DoE) focused on comparing different steel material models that differ in the amount of toughness they capture. A DoE with 45 runs was executed per material model to determine how each material model affects the prediction of the critical pressure of a pipe with an axial crack. The steel material models were:

1. Elastic-perfectly plastic (EL-PP).
2. Ramberg-Osgood (R-O) plastic strain hardening with perfect plasticity beyond the ultimate tensile stress.
3. Elastic/power-law plastic hardening, with Bao-Wierzbicki triaxiality-dependent damage (GTI steel model).

The critical pressure in each simulation run was determined by the limit state. The limit state, as defined by ASME FFS-1, is the last converged step in an FEM simulation. The limit state corresponds to the maximum pressure applied on the pipe before the simulation could no longer progress due to excessive deformation rate (virtual pipe rupture).

A comparison of the first two material models is provided in this report, where the R-O model shows a 4-19% increase in the limit state versus the EL-PP model, as expected.

The GTI steel model was validated on two full-scale pipe burst tests, each representing a different flaw type: corrosion wall-loss and V-notch gouge. The simulation of the respective burst tests both predicted the burst pressure within 1%. However, the GTI steel model is not included in this report due to numerical convergence issues associated with the damage model and thin crack propagation, which led to lower limit states than the more conservative EL-PP and R-O models. Improvements in the GTI steel model formulation are needed to increase its stability during damage propagation.

Multi-Modal NDE Sensing Techniques Phase 3 Report

MSU converted their FEM simulation models to the COMSOL Multiphysics platform. This step was taken to allow GTI and MSU to run their respective FEM simulations on the same models using the same multi-physics platform. This will ensure maximum coherence between models that will improve uncertainty quantification that accounts for uncertainty in characterization of the defect configuration from NDE scans and uncertainty in the limit state of a pipe given a particular defect characterization. MSU stepped through a simulation process for Magnetic Flux Leakage (MFL) simulation & analysis in the COMSOL platform.

Model-based Framework Phase 1 Report

MSU demonstrated a transfer learning process where prior information from a baseline detailed MFL scan of a pipe run at slow speed is used to improve the process of extracting useful data from a subsequent scan run at high speed. The high-speed scan is noisy, and it is difficult to extract weak signals from the collected data. The transfer learning process greatly facilitates the process of characterizing changes in the defect configuration over time using high-speed scans of the pipe.

1st Data Analysis Methods Progress Report

There has been enough work completed by all three collaborating institutes for us to take a step back, review the results, and think about the appropriate data analysis methods to apply to the project results. This process has led to a slightly revised project framework relative to the framework laid out in the original proposal. The data analysis review process we worked through is laid out in bullet form below:

- We have reviewed the fitness for service standards and relevant additional standards they reference to ensure we capture all relevant data elements, how the standards address uncertainty in the data, and which output parameter will be most useful,
- We have developed a clear statement of the objectives of the data analysis task,
- We have identified where these data analysis objectives will be useful to the industry,
- We have carefully reviewed project results to-date and used the insights gained to revise the data analysis framework,
- We are now well positioned to apply Monte Carlo analysis and other probabilistic data analysis tools to ensure that we meet our project objectives

Next Steps

- Convene a web meeting with the Technical Advisory Panel (TAP) to:
    - Review the method development that has been the focus of the project in the early stages
        - Material testing
        - Damage models
        - Uncertainty quantification
        - NDE simulation
        - Full scale validation testing
    - Solicit guidance on what the project focus should be given the analysis methods we have developed
    - Solicit input from the TAP as to what the most useful form of guidance would be for the industry
- Develop a survey to send to the TAP in advance of the web meeting to organize the questions pertaining to focus the project team would like to have answered by the TAP
- Move into high gear on FEM simulation of interacting defects
- Develop the data analysis modules to apply to the simulation results